Frequently Asked Questions about Integration of e+a Motors & Generators

Shafts for e+a rotors – Guidelines on Permeability, Materials & Shaft ID (for hollow shaft applications).

Permeability - Shaft material selection is an important issue since the shaft itself is part of the magnetic circuit of the rotor. The shaft material must be ferro-magnetic (i.e. a magnet sticks to it). The primary specification is that the relative permeability (**μ_r**) of the shaft needs to be at least 100 or higher (the higher the better):

μ_r needs to be >100.

Permeability is the ability to support formation of magnetic fields in a material and is measured in *H/m (henries/meter)* or *newtons/ampere^2 (N/A^2)*.

The permeability of free space μ_0 (the permeability constant or the magnetic constant) is

$\mu_0 = 4\pi\ 10^{-7}$ *(H/m)*

$\approx 1.257\ 10^{-6}$ *(H/m, N/A^2)*

Relative Permeability is the ratio of the permeability of a specific medium to the permeability of free space μ_0

$\mu_r = \mu / \mu_0$

where

μ_r *= the relative permeability*

μ *= permeability of the medium (H/m)*

The lowest relative magnetic permeability of a paramagnetic material is 1.0 - and the magnetic response of the material is the same as 'free space' or complete vacuum.

Examples of Shaft Material Types - Table 1 below lists some known shaft materials that have been successfully used in e+a rotors by customers. The actual shaft material used depends on many factors so it is critical to evaluate the characteristics of each of the materials below against the specific system requirements. It is the responsibility of the customer to choose the material for the shaft. If there is a question on a particular material type please contact e+a Technical Support.

The Table below is indexed by the EN (CEN)/European specification number of steels (EN Mat. No.); also shown is the EN Composition value and a potential ANSI/SAE equivalent. The solid specification is the EN Mat. No.; all other information were derived from various compatibility tables and are not guaranteed to be exact. Other materials are possible, and a generalized list of Material Permeability is shown in Table 2 for reference:

Table 1 – Successful Shaft Materials

EN (European CEN)	EN Composition	ANSI/SAE (USA)	GB/T (China)
1.2312	40CrMnMoS8-6	P20+S	
1.4031	X39Cr13	420	
1.4122	X39CrMo17-1		
1.4542	X5CrNiCuNb-16-4	17.4 PH	05Cr17NiCu4Nb
1.4548	X5CrNiCuNb-17-4-4	630	
1.5752	15NiCr13	3415, 3310	
1.5919	15CrNi6	3115	
1.6655	32NiCrMo12-5	A723	
1.6582	34CrNiMo6	4340,4337	
1.7131	16MnCr5	5115	
1.7139	16MnCrS5	5117	
1.7149	20MnCrS5	5120	
1.7225	42CrMo4	4140	
1.7227	42CrMoS4	4140	
1.8519	31CrMoV9		

Table 2: Generalized List of Material Permeabilities

Medium	**Permeability** **- μ -** ***(H/m)***	**Relative permeability** **- μ / μ_0 -**
Air	$1.25663753\ 10^{-6}$	1.00000037
Aluminum	$1.256665\ 10^{-6}$	1.000022
Austenitic stainless steel[1)]	$1.260\ 10^{-6}$ - $8.8\ 10^{-6}$	1.003 – 7
Bismuth	$1.25643\ 10^{-6}$	0.999834
Carbon Steel	$1.26\ 10^{-4}$	100
Cobalt-Iron (high permeability strip material)	$2.3\ 10^{-2}$	18000
Copper	$1.256629\ 10^{-6}$	0.999994
Ferrite (nickel zinc)	$2.0\ 10^{-5}$ – $8.0\ 10^{-4}$	16 – 640
Ferritic stainless steel (annealed)	$1.26\ 10^{-3}$ - $2.26\ 10^{-3}$	1000 – 1800
Hydrogen	$1.2566371\ 10^{-6}$	1
Iron (99.8% pure)	$6.3\ 10^{-3}$	5000
Iron (99.95% pure Fe annealed in H)	$2.5\ 10^{-1}$	200000
Martensitic stainless steel (annealed)	$9.42\ 10^{-4}$ - $1.19\ 10^{-3}$	750 – 950
Martensitic stainless steel (hardened)	$5.0\ 10^{-5}$ - $1.2\ 10^{-4}$	40 – 95
Nanoperm	$1.0\ 10^{-1}$	80000
Neodymium magnet	$1.32\ 10^{-6}$	1.05
Nickel	$1.26\ 10^{-4}$ - $7.54\ 10^{-4}$	100 – 600
Permalloy	$1.0\ 10^{-2}$	8000
Platinum	$1.256970\ 10^{-6}$	1.000265
Sapphire	$1.2566368\ 10^{-6}$	0.99999976
Superconductors	0	0
Teflon	$1.2567\ 10^{-6}$	1

Medium	Permeability *- μ -* *(H/m)*	Relative permeability *- μ / μ₀ -*
Vacuum *(μ_0)*	**$4\pi\ 10^{-7}$**	**1**
Water	$1.256627\ 10^{-6}$	0.999992
Wood	$1.25663760\ 10^{-6}$	1.00000043

1) Permeability of austenitic stainless steels is not like ferritic, martensitic and duplex stainless steel. Austenitic steel can be classed as paramagnetic with relative permeability approaching 1.0 in the fully austenitic condition. The low permeability enables austenitic steel to be used where a non-magnetic material is required.

Hollow Shafts – Shafts used in e+a motors can be hollow, and the rule of thumb is that the maximum hollow shaft ID is no more than 60% of the shaft OD, without having an impact on the interference fit. For a special requirement contact e+a Technical Support and they can do an FEA analysis to see if a particular shaft ID is possible with your shaft specifications.

For Hollow Shafts: **Shaft ID < 60% Shaft OD**

Temperature – Rotor, Stator, Cooling

Rotor Temperature – Rotor temperature is a critical parameter as it can ultimately determine how much power the motor/generator puts out, and it can have a significant effect on the motor/generator lifetime. The maximum temperature a rotor can function at depends on whether it is an induction or Permanent Magnet (PM) machine. PM motors are limited by the temperature capability of the rare earth magnets used in the rotor, and whether the rotor overwrap is Carbon Fiber composite or a MEBA steel sleeve. Carbon Fiber overwraps are insulators so the magnets run hotter and much of the rotor heat goes out through the shaft and into the bearings. In general a good rule of thumb is to keep the rotor temperature below the maximum temperature allowed by the stator insulation material, which is 155°C for Class F stators and 180°C for Class H stators. The lower the rotor temperature the better.

Stator Slot Temperature - The primary motivation to keep temperatures low inside a motor/generator is an increase in motor life. As an example, the stator slot insulation inside a Class H stator is rated to 180°C. At this temperature the lifetime of this insulation is approximately 10,000 hrs. For every 10°C that the inside temperature of the stator is lowered (long-term constant temperature), the lifetime of the machine doubles. For example, if the inside of a Class H stator is kept at 150°C, then the approximate life of the stator is 80,000 hrs.

PM Rotor Sleeves (Carbon Fiber Composite) – For PM rotors with Carbon Fiber sleeves the rotor ID is an internal taper (50:1). By pushing the rotor onto the shaft taper the rotor expands and the carbon fiber sleeve, which is placed on top of the magnets will be preloaded to keep the magnets in place at full speed. The push-on distance is provided by e+a as part of the delivered rotor drawings, and takes into account that the carbon fiber material has a negative temperature coefficient; so at increasing speeds (and thus increasing temperatures) the carbon fiber sleeve gets progressively tighter. It is important to push the shaft to at least the minimum Push-On Distance specified in the documentation to get the correct preload (tension) onto the carbon fiber sleeve. This retaining sleeve is responsible for keeping the magnets in place at full speed when the centrifugal forces are the highest. If the rotor is not pushed on the specified distance the magnets will move off the shaft and cause (dynamic) imbalances.

For additional information regarding inserting a shaft into the rotor bore of a PM system download the PM assembly manual from the Support and Downloads page at www.eandaUSA.com.

Axial Rotor and Stator Alignment - the "center of stator core" mark on the PM rotor points to the axial center of the rotor magnet, which must align with the axial center of the stator core during assembly. The actual alignment needs only to be within ±3 mm. Misalignment starts to effect power when it is more than 5mm out of center, and in addition, an axial magnetic pull is created.

Rotor Heating Caused by VFD/Inverter - Conventional variable speed drives rely on motor inductance to filter the inverter’s switching waveform to produce a relatively smooth motor current. The remaining switching current through the motor is referred to as “ripple current”, as it appears as a triangular signal that ripples thought the fundamental waveform. The simulated motor current waveform, shown below, has approximately three percent current ripple. This ripple current causes high frequency magnetic flux, which in turn, causes losses in a motor/generator by creating eddy currents in the rotor, in permanent magnets attached to the rotor, and in the stator. None of the ripple current in a Variable Speed Drive’s (VFD’s) waveform produces torque; it all ultimately goes to producing losses in the form of heat in the rotor and stator. These losses are exponentially related to frequency, and can be very significant, even though the ripple current does not appear to be large in relation to the waveform fundamental.

To maintain acceptable rotor losses, especially in applications involving permanent magnet motor/generators, it is recommended that the Total Harmonic Distortion (THD) be 5% or less.

Total Harmonic Distortion from Controller/Inverter < 5%

For standard 2-level inverters this will likely require a “sine filter” to be placed between the inverter and motor to provide further ripple current reduction. The cutoff frequency of this filter must be placed sufficiently above the motor's fundamental frequency to avoid excessive drive losses, but also sufficiently below the drive's switching frequency to effectively reduce the ripple current. The use of a sine filter between the motor/generator and a typical two-level inverter causes filter insertion loss and filter power loss, as well as the increased cost and bulk of the filter. The insertion loss reduces the voltage available to the motor/generator requiring a lower torque constant winding and therefore a higher current inverter for a given motor/generator power level. In addition to sine filter inductor losses resistors are needed to damp resonance. The power loss in these elements can be significant and the effect is to reduce two-level inverter efficiency in many systems by several percent.

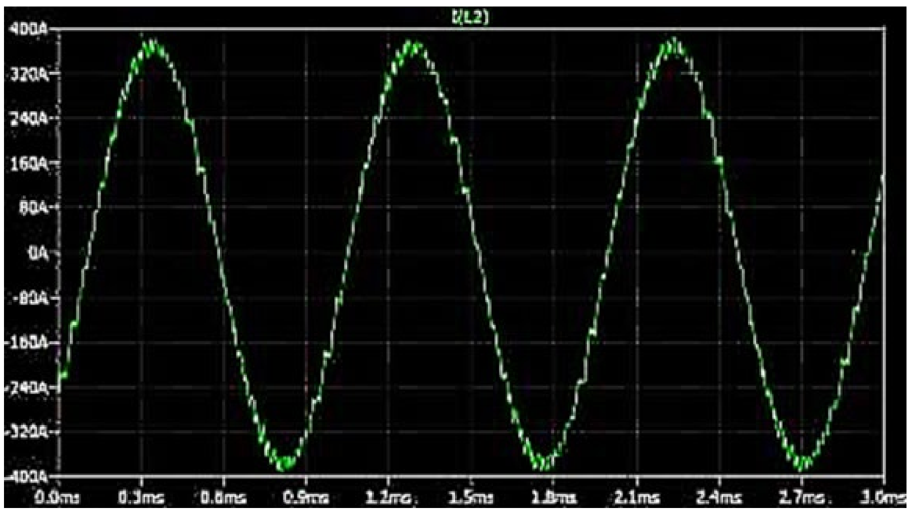

Figure1: Ripple Current on Simulated Motor Current Waveform With Two-Level Inverter

Level Inverter (MLI) has fewer switching losses and lower filtering requirements than conventional two-level inverters. Each time a switch changes state, there is an energy loss related to the change in voltage level. That change level for a three-level MLI is one-half the amount of that of a two-level inverter, which results in approximately 50 percent less switching loss. Additionally, the 50 percent reduction in switching voltage level also reduces the filtering requirement by 50 percent. The waveform in Figure 2 shows simulated motor phase current when driven by a three-level MLI with a sine filter. The ripple current, which is less than 0.5 percent of the fundamental, is almost undetectable by eye.

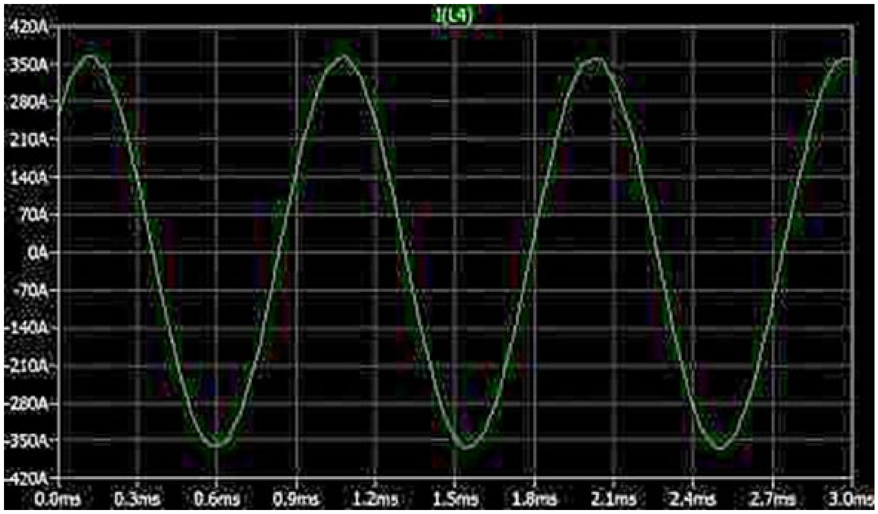

Figure 2: Ripple Current on Simulated Motor Current Waveform with Three-Level MLI & Sine Filter

In an Inverter for a PM Generator, since power flow is bidirectional, a conventional diode rectifier is unsuitable for converting between the AC grid voltage and motor drive's DC link voltage.

It is recommended to use instead an Active Front-End (AFE), which is an inverter that synchronizes to the utility grid and is controlled to produce sinusoidal currents in-phase with the sinusoidal grid voltages.

e+a recommends that customers perform an electrical insulation test to make sure that the stator is correctly mounted and that the wire routing, connectors are properly assembled and safe.

Prior to shipping the machine e+a recommends performance a high voltage test to ensure that there is no electric insulation fault and the machine can be safely operated.

The high-voltage (HV) test must be done between the motor phases (all wires connected together) to the ground. It is important to short-circuit the thermal sensors (wires connected to ground) to avoid damaging the probes during HV test.

DIN standard EN60034-1 prescribes the correct voltage level for the tests:

Arcing on Bearing Housing – In some installations arcing can occur, especially in the bearing housing. This arcing issue is usually caused PWM Inverter common mode currents. This is a very well known problem with high speed machines, especially when the shaft is not connected to ground (e.g. when ceramic ball bearings or Active Magnetic Bearings (AMB's) are used); the phenomena is referred to as Bearing Currents. The arcing is typically the result of PWM Inverter set up, cable set up, connectors etc... One solution is to have the stator lamination stack, housing and the shaft connected to ground (all the same potential). Please note that solid conductors like the housing are very poor conductors of high frequency signals.

Make sure the stator cooling jacket is connected to ground using a Litz wire between the cooling jacket and the housing. Gliding seats with O-ring seals may isolate the stator from ground.

Below is a link to general information about this phenomena.
https://library.e.abb.com/public/8c253c2417ed0238c125788f003cca8e/ABB_Technical_guide_No5_RevC.pdf